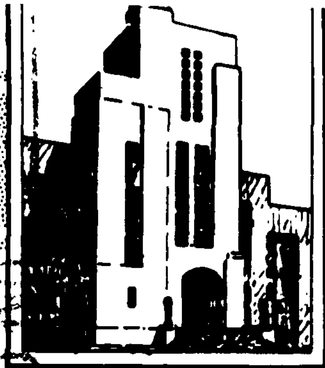

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN

HYDROMECHANICS

AERODYNAMICS

STRUCTURAL MECHANICS

APPLIED MATHEMATICS

NEW METHODS FOR DETERMINING THE
LOSS FACTOR OF MATERIALS AND SYSTEMS

by

Fred Schloss

HYDROMECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

April 1963 Report 1702

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ABSTRACT

Two new methods, one of which uses mechanical impedance techniques, are described for measuring the loss factor of materials and systems at any arbitrary frequency in frequency range from 10 to 10,000 cps. The accuracy of these methods increases with increased damping and therefore the methods complement other methods which are most accurate for low values of damping. The apparatus and accuracies are discussed.

INTRODUCTION

It is becoming increasingly important and desirable to realistically represent and measure the damping possessed by materials and composite structures. High-damping materials are playing a widening role in the ship silencing program. As a result, the measurement of the damping parameters using common methods operating near resonances[1] has become increasingly difficult, since resonances are hard to establish. It is the purpose of this paper to introduce two methods, one of which, although old, makes use of a relatively new tool - mechanical impedance. Since the accuracy of these methods increases with increased damping, they complement other methods which are more precise for lightly damped materials and structures. Further, using one of these methods, the loss factor of the system may be automatically plotted continuously as a function of frequency in very little time in the range from 10 to about 1000 cps. The change of loss factor with increasing steady and alternating stresses may be evaluated.

DEFINITIONS

Mechanical impedance is the complex ratio of the force phasor to the velocity phasor. If the two phases are determined at the same point, the ratio is defined as the driving point impedance, and if they are determined at different points, the ratio is defined as the transfer impedance.

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[1]References are listed on page 7.

The loss factor of the system (η_s) is the ratio of the magnitude of the real to imaginary part of the complex impedance.

ADMINISTRATIVE INFORMATION

This paper is based on investigations performed at the Taylor Model Basin, which were sponsored by the Ship Silencing Branch of the Applied Research Division, the Bureau of Ships, under Project S-F013 11 01.

METHOD I - BLOCKED TRANSFER IMPEDANCE TECHNIQUE

It is convenient to characterize simple damped structures or materials by considering the element as a mechanical black box with two accessible points. If the motion of each accessible point is restricted so that it can be described by a single space variable, then the mechanical behavior of the black box when placed in a system can be completely calculated provided three impedances measured at the accessible points of the box are known. The phase angle φ of one of these impedances - the transfer impedance with one end blocked - is simply related to the loss factor of the system η_s of frequencies much below the first standing wave frequency f_1 by

$$\left|\cot \varphi\right| = \eta_s$$

The loss factor of the system is the ratio of the magnitude of the real to imaginary part of the complex impedance. By this method the loss factor can be determined <u>continuously</u> as a function of frequency.

Two conditions must be satisfied to insure that correct readings of the blocked force are obtained from the force gage:

(1) The impedance of the force gage must be much greater than the impedance of the "massy" appendages between the force gage and the specimen.

(2) The driving point impedance of blocking structure must be much greater than the blocked impedance measured.

The first condition imposes an upper frequency limit, the second a lower frequency limit. Whether or not these conditions are satisfied may easily be determined experimentally.

The temptation is to determine the loss factor from the driving

point impedance of the blocked compliant material. Such a measurement, however, severely limits the frequency range over which continuous measurements may be made since the true driving point impedance of the compliant material decreases with frequency, whereas the measured driving point impedance includes the impedance of appendages at the free end, which usually increase with frequency. Thus, unless the force gage is exceedingly light and attached directly to the compliant material, errors may be introduced at comparatively low frequencies. This difficulty is avoided by measuring the force at the blocked end which is the same as the force at the free end of the material itself provided the frequency is low enough that the material can be treated as a massless system (which is the case where f is less than $0.25f_1$, where f_1 is the frequency of the first standing wave). In other words, the transfer impedance is not in any way influenced by attachments to the free end of the compliant material even at the resonance of the appendages at the free end with the compliant material.

The phase angle φ of the transfer impedance gives a direct measure of loss factor, viz.,

$$|\cot \varphi| = \eta_s \quad (f < 0.25\, f_1)$$

$$(50\, \eta_s = \text{percent of critical damping})$$

Although different tools are used for measurements, the above formula is a restatement of the well known equation for the loss factor (loss tangent) $\eta_s = \tan \alpha$ where α is the angle between the applied force and resulting displacement. If the damping material can be physically separated from the structure, e.g., "Aquaplas," and is not built into the structure, e.g., laminated beams, the transfer impedance technique may be used to characterize the damping material separately from the structure onto which it is attached, provided that the damping mechanism is not changed. Since

$$\cot \varphi = \eta_s = \frac{\omega R}{K + K_D} \quad (f \ll f_1)$$

where R is the resistance of the damping material, K is the stiffness of the undamped structure, and $K + K_D$ is the stiffness of the damped structure and since $\cot \varphi$, K, and $K + K_D$ can be evaluated separately, all

dynamic properties of the damping material are available. If the damping material is to be applied to any structure in the same manner and if the stiffness of the undamped structure is known, then the loss factor of the damped structure may easily be calculated.

It is possible, although not attempted here, to compute the loss factor at any frequency from the blocked transfer impedance measurements for rather idealized shapes. However, whenever the system does not act as a lumped system, the computations are difficult and the required precision in the measurements is much greater.

METHOD 2 - REACTANCE NULLING TECHNIQUE

Since the occurrence of standing waves limits Method 1 to frequencies below about 2000 cps, another method had to be found for higher frequencies. It is well known that the loss factor of a single-degree-of-freedom system may be calculated from $\frac{d\varphi}{df}$ very near a resonance or antiresonance, where φ is the phase angle between the motions at both ends or of the point impedance

$$\eta_s = \frac{2df}{d\varphi \cdot f} \approx \frac{2\Delta f}{\Delta\varphi \cdot f}$$

where f is the frequency. In this method, the distributed system is treated experimentally in terms of the equivalent single-degree-of-freedom system. The mechanical resonances may be hard to find and excite at the higher frequencies with highly damped structures. The novel feature of this method is to create electrically a pseudoresonance by electrically cancelling the reactive component in one of the signals and then determining $\frac{\Delta\varphi}{\Delta f}$ near this pseudoresonance. This is equivalent yet simpler than to tune the system mechanically by attaching springs or masses. Fortunately, the necessary instrumentation was already available (although used for a different purpose); it is described in Reference 2. By this method, the loss factor may be determined at any frequency; however, the method cannot be performed by automatic instrumentation and a great amount of care and skill is required in the measurement. The experimental error is greater than in Method 1.

EXPERIMENTAL CONSIDERATIONS

DETERMINATION OF UPPER FREQUENCY LIMIT FOR METHOD I

Whether or not a compliant material acts as a lumped system may be determined experimentally from inspection of the transfer impedance plot or from calculated or measured values of the frequency of the first standing wave. Experimental results show that $\cot \varphi = \eta_s$ provided f is less than 1/4 f_1; f_1 may be calculated by considering the specimen clamped at the driven end and hinged or clamped -- as the case may be -- at the blocked end. For example, for an undamped rectangular beam of length 2L and thickness t driven in the middle and hinged at the ends, f_1 is $0.71 \frac{t}{L^2} c$, where c is the velocity of sound in the material. If the upper frequency of interest is 1000 cps (f_1 = 4000 cps) $\frac{t}{L^2}$ should be at least 0.0282 for an aluminum or steel beam (t and L in inches). A beam having a full length of 6 in. and a thickness of 1/4 in. may be chosen. Applying the damping material does not reduce f_1.

END EFFECTS

The damping introduced by attachments to the ends of the specimen must be much smaller than the damping of the specimen. The magnitude of the damping introduced by the end effects may be measured by using undamped structures. When rings and beams (as shown in Figures 1 and 2 are used without the damping treatment, the loss factor introduced by the ends is less than 0.003. Therefore, no measurements can be made with accuracy for specimen having loss factors below 0.03. Errors due to end effects can be avoided in Method 2 by not blocking the system.

VERY LOW FREQUENCY MEASUREMENTS FOR METHOD I

At very low frequencies, the blocked transfer impedance is high and it may be difficult to make measurements because of coherent electrical noise in the motion transducer caused by ambient vibration levels. Noise does not affect the precision of the measurements when the instrumentation described in Reference 2 is used except for the noise in the pass band

of the filters. To reduce the ambient vibration level, the blocked end may consist of a heavy mass mounted on a soft suspension. The resonant frequency of the suspension system should be below one-half of the lowest frequency of interest, and the impedance of the mass should be at least 10 times the impedance of the specimen at the lowest frequency of interest. In other words, the driving point impedance of the suspended mass should be at least 10 times the blocked impedance of the specimen.

MEASURING ACCURACY OF TRANSFER IMPEDANCE TECHNIQUE - METHOD I

Table 1 shows the accuracy of the measuring equipment and the necessary precision of the measurements for a given loss factor. Greater accuracy can be obtained with higher loss factors.

ACCURACY OF REACTANCE NULLING TECHNIQUE - METHOD 2

In this method, great care must be exercised in measurements. The smaller the frequency range over which the change in phase angle is observed, the more accurate the measurement, except that for very small Δf's an error is introduced by frequency drift of the oscillator during measurements. From experimental results, the ratio $f/\Delta f$ of 100 to 200 was found to be most suitable. Measurements are difficult at low frequencies because of the small Δf required.

APPARATUS AND RESULTS

Figures 1 and 2 show the apparatus used with a damped ring and a laminated beam. An accelerometer housed in an impedance head was used as the motion transducer.

Figures 3 and 4 show the transfer impedances and the loss factor of the ring. It may be seen that the loss factor changes abruptly at the same frequency (750 cps) at which there is a change in the slope of the transfer impedance. The measurements of the loss factor and transfer impedance up to 750 cps were taken in about 15 min. Above 750 cps, Figure 4 shows values of the loss factor obtained from the reactance nulling technique in about 1 hr.

Figures 5 and 6 show the loss factor of a damped plate and a

laminated beam. The beam is blocked at two ends, but the force is measured only at one end as shown.

Figure 7 shows the variation of the loss factor as a function of driving amplitude at a fixed frequency.

REFERENCES

1. Geiger and Hamme, "The Concept of Damping of Structureborne Sound and Vibration for Noise Control," Report No. USN-1, April 1961. Prepared for BuShips under Contract NObs 73549, NS-713-212(S-F013 11 01, Task 1353).

2. Schloss, F., "Recent Advances in the Measurement of Structural Impedance," DTMB Report 1584 (January 19, 1963). Also published as SAE paper 426B, October 1961.

TABLE 1

Accuracy of the Measuring Equipment

Loss Factor	Accuracy in Measurement of Phase Angle Required for Errors of Less than 10 Percent In Determination of Loss Factor degrees	Actual Accuracy in Phase Angle Measuring Equipment degrees
0.001	0.006	0.06
0.01	0.06	0.06
0.1	0.6	0.12
0.3	1.7	0.35

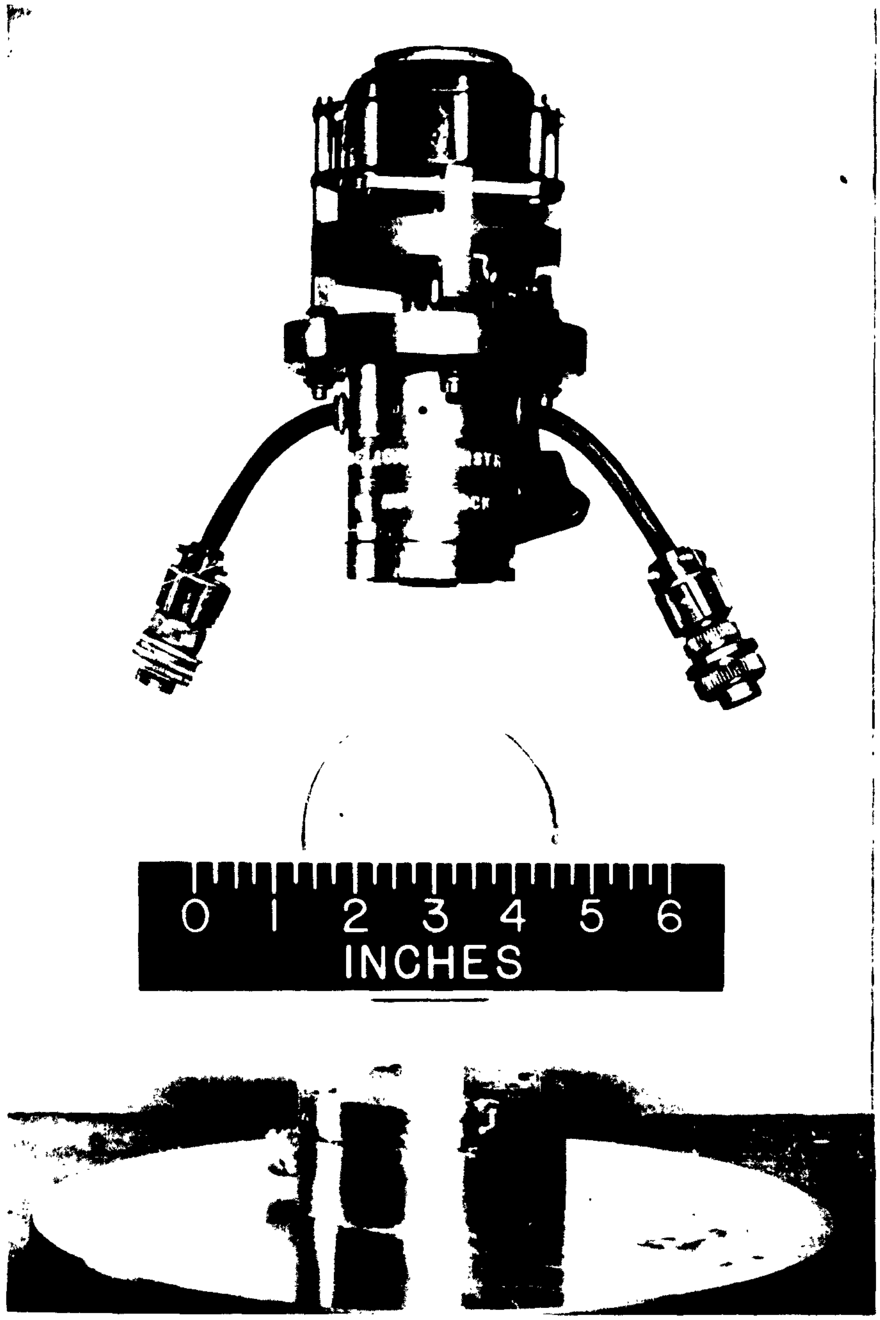

Figure 1 - The Apparatus Used with a Damping Ring

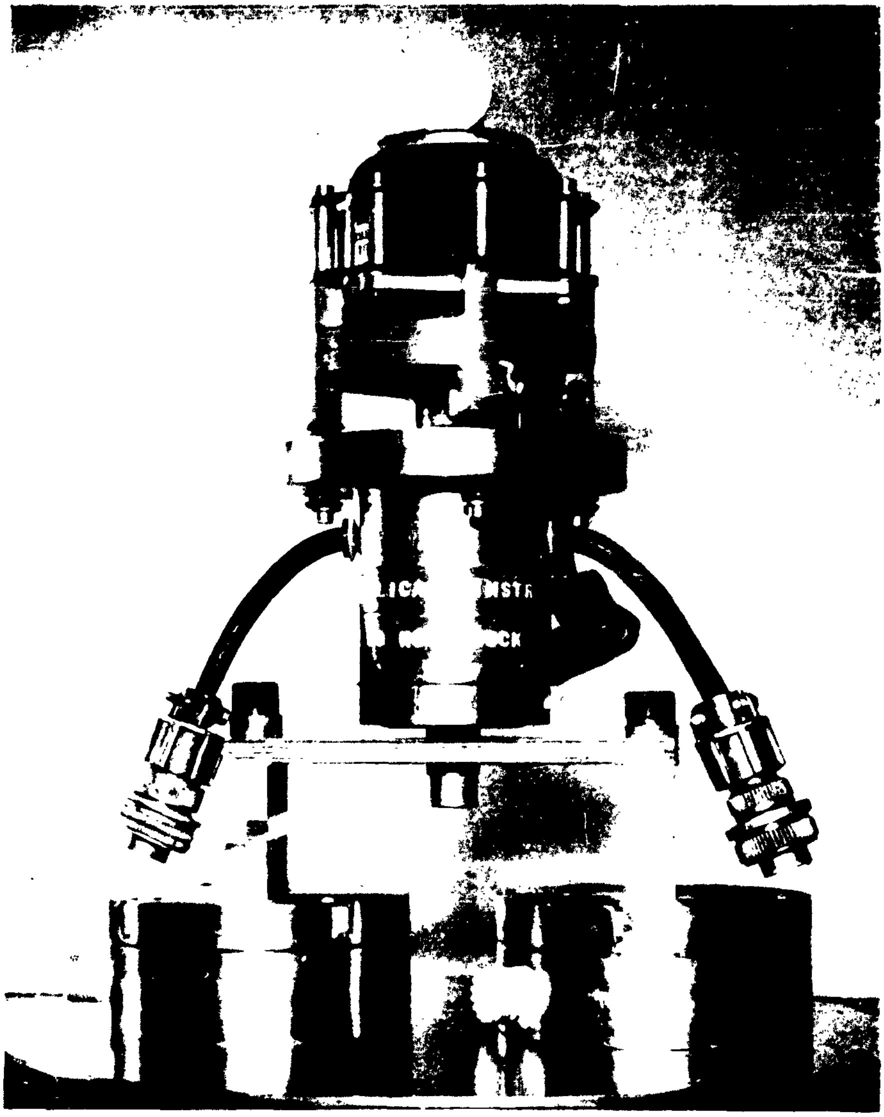

Figure 2 - The Apparatus Used with a Laminated Beam

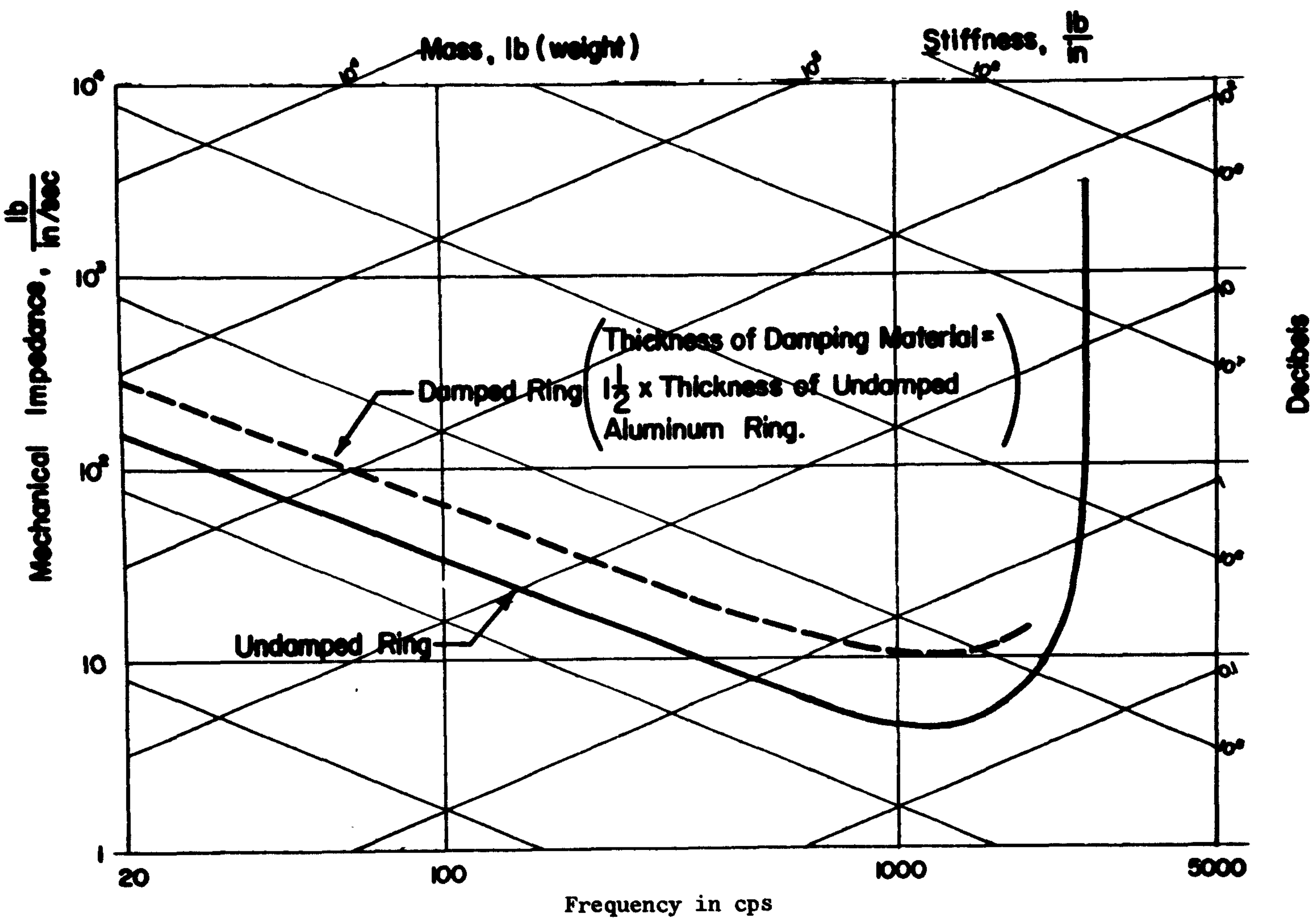

Figure 3 - Transfer Impedance of Undamped and Damped Structure

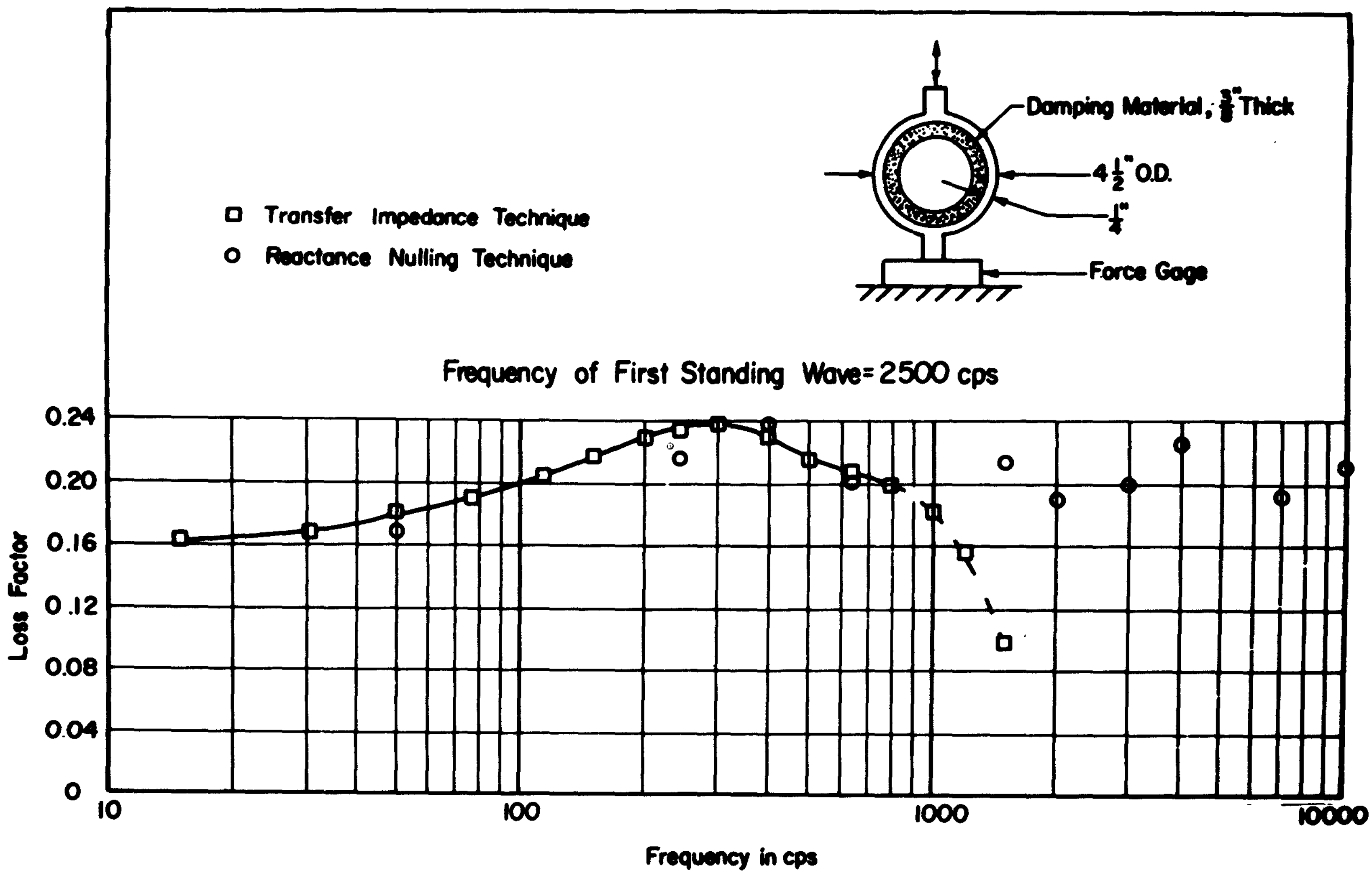

Figure 4 - Loss Factor of a Damped Aluminum Ring

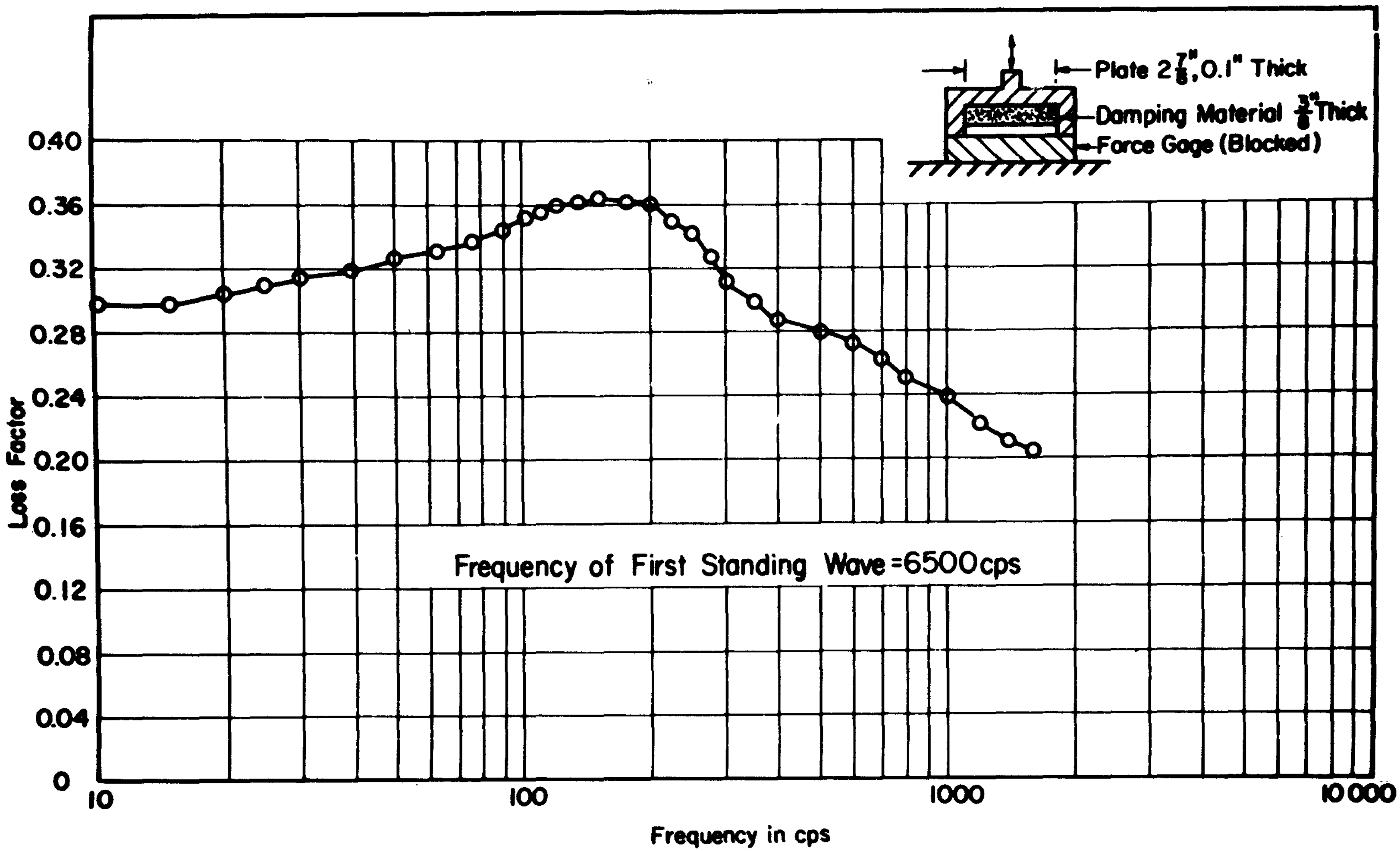

Figure 5 - Loss Factor of Damped Round Plate Driven at Center and Supported at Periphery

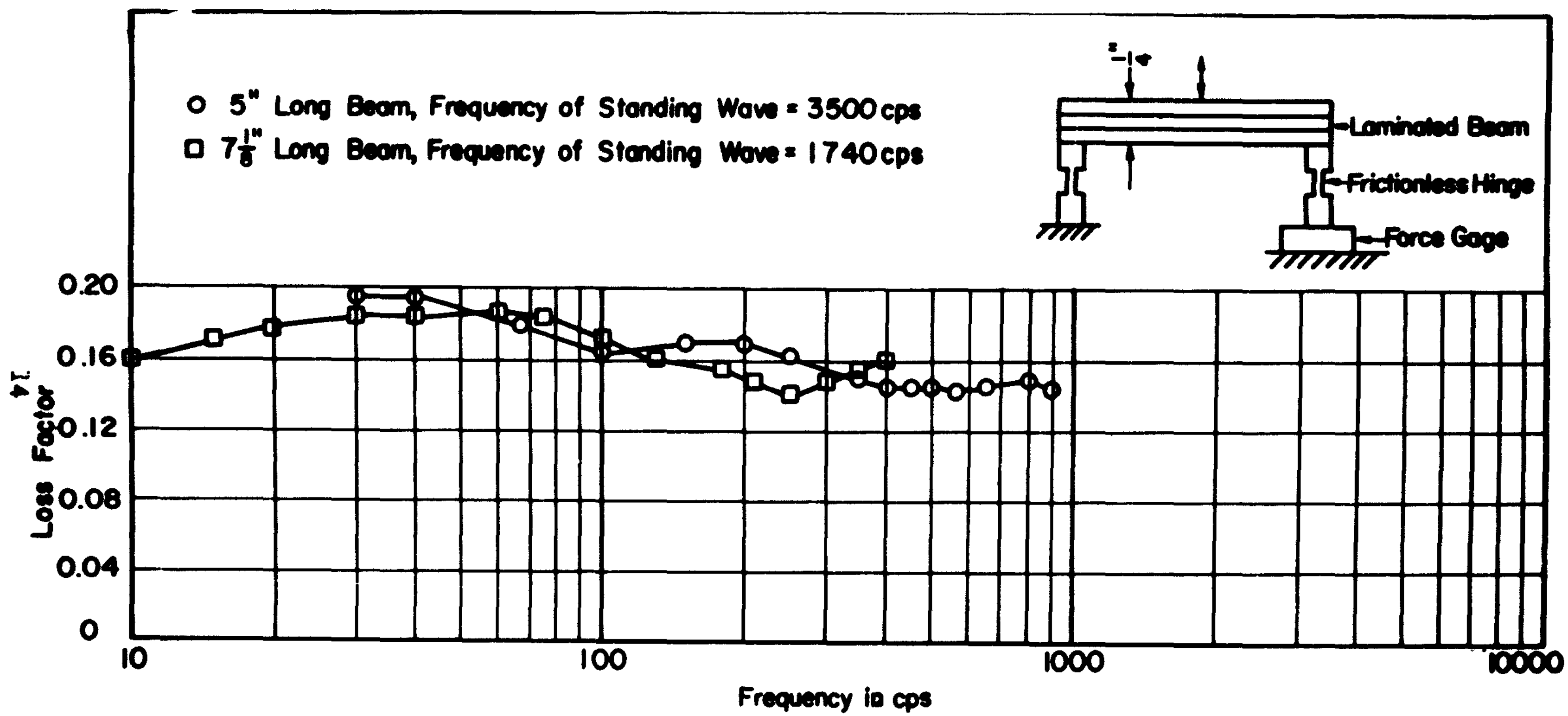

Figure 6 - Loss Factor of a Laminated Beam Driven at Center at a Constant Acceleration Level of 0.01g and Supported at Ends

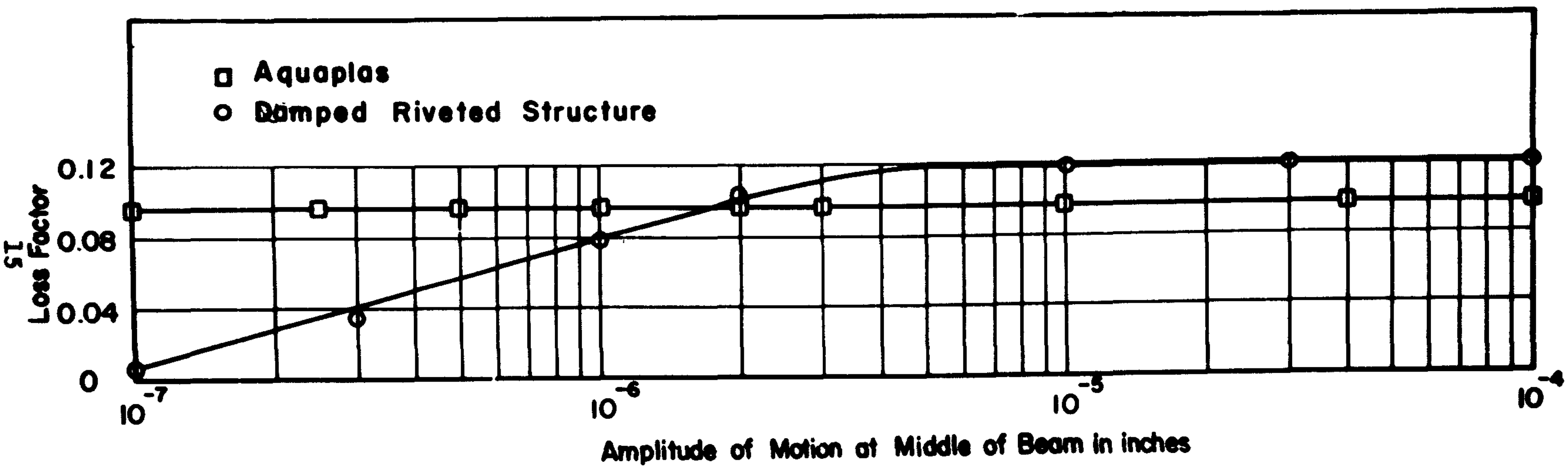

Figure 7 - Linearity of Two Damped Beams with Different Damping Mechanisms

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